Lecture17	Krane	Enge	Cohen
photonuclear		13.14	13.10

Lecture 22

Photonuclear Reactions

I want to talk about one area of nuclear physics that is currently researched in this School. It is an area where we have made a small but not insignificant contribution to the field.

Research in this field only became feasible with the invention of electron accelerators capable of producing high energy photons. The first was the betatron in 1948, and by 1950 researchers here had built one at Melbourne. After 1960 and until about 10 years ago we had in-house a 35 MeV betatron, which was the basis of most of the photonuclear program. However even then much of our work was done overseas at Los Alamos Nat Lab in the USA (Manhattan project), Livermore Nat Lab, in Japan at Sendai and currently at Lund University in Sweden. Since the closing-down of the Betatron, we have worked exclusively at overseas facilities, where we have access to photons of higher energies and with excellent specs.

In photonuclear reactions we have a method of studying the nucleus, and the nuclear force, using the EM interaction. That is, we are only interacting with the charges and currents in the nucleus, yet studying the intrinsic nuclear properties.

In all nuclear reactions we are concerned with the transition

$$\gamma + |i\rangle \rightarrow |f\rangle$$

In photonuclear reactions the hamiltionian for the system involves the nuclear hamiltonian and the EM one

$$H = H_{nucl} + H_{em}$$

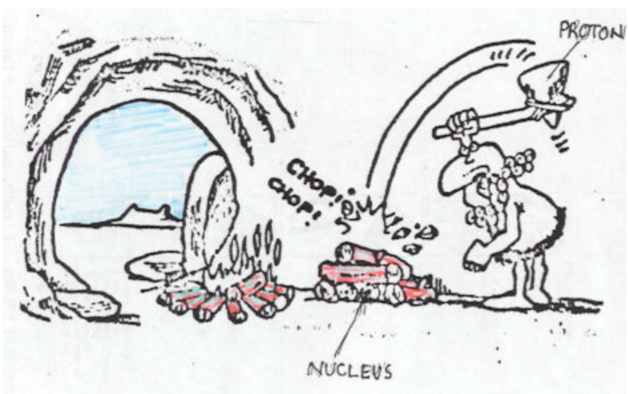
H_{nucl} describes the nuclear system containing the initial and final states, and H_{em} describes the EM interaction that couples the initial and final states.

The transition amplitude for this reaction is

$$M_{fi} = \langle f | H_{em} | i \rangle$$

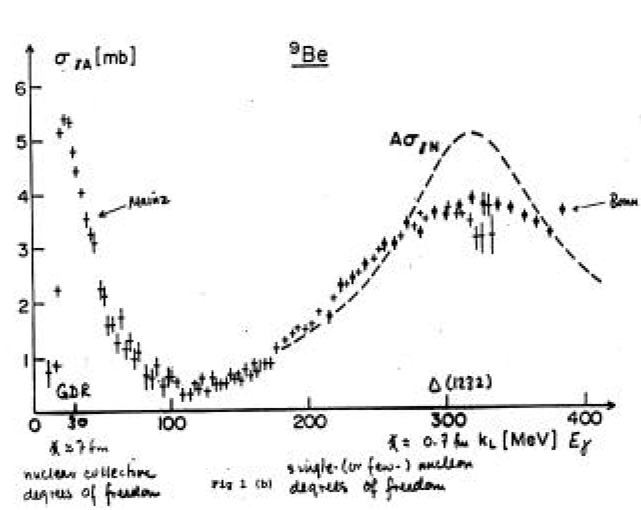
The real problem is not the EM interaction in the above equation, but the wavefunctions for the initial and final states, are formulated in terms of nuclear models, and this is the ultimate limitation.

H_{nucl} is generally written as $H_{nucl} = H_{SM} + R$. This means that the wavefunctions are determined to first order by the shell model we have studied, plus anything left over, which is incorporated into R, the residual interaction.. Note that it is the R that leads to the admixing of the wavefunctions that we discussed last lecture. The ultimate aim is to determine the nature of this residual or short-range nucleon-nucleon force. This is the bit we want to know about.



The advantage of the photon as the interacting particle is that the EM interaction is orders of magnitude weaker than the N-N interaction, so that the nuclear system is not significantly perturbed by the interaction that takes if from the initial to the final state. Equally importantly the EM interaction is completely known via quantum electrodynamics.

In essence what we want to do is to perform the experiment (that is create the final state) and compare the results with calculations done using some model. The differences between prediction and observation should lead us to an understanding of the residual interaction.



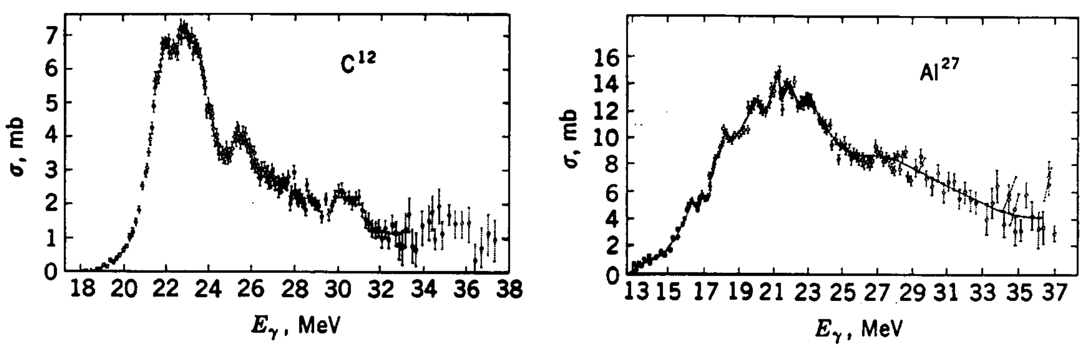
There are several clear regions studied in photonuclear physics

- the low energy region, below the nucleon emission threshold
- the GDR region
- the region above the π-meson threshold
- the intermediate energy region between the previous two.

These are illustrated in the vugraph which shows the absorption cross section for photons between a few MeV and 1000 GeV.

Below the nucleon emission threshold individual nuclear states are photo-excited, and having no other decay probability, decay back to the GS either directly or by cascades determined as we discussed several lectures ago.

The Giant Dipole Resonance region . This broad resonance occurs at about 12 MeV for heavy nuclei like Pb, up to 22 or so for light nuclei. It can be pictured as a collective oscillation of the entire nucleus, set up by a resonance between the frequency of the EM wave and the natural frequency of the EM wave. On the other hand it might be pictured as the excitation of a multitude of overlapping quantum states in the nucleus which are populated by absorption of a photon .



The wavelength of the EM wave at 10-20 MeV is about 40 fm, much bigger than the radius of the nucleus. So that the charges in the nucleus respond to the external stimulus and are forced into oscillation up and down. When the frequency is resonant, the amplitude of oscillation is large (the absorption cross section a maximum).

For lighter nuclei the phenomenon can be modelled as exciting protons from SM orbits in the GS WF to orbits at higher energy corresponding to the energy of the exciting photon. As we have discussed the probability for a γ transition depends on the multipole, and the most likely is an E1 transition. Hence this resonance involves E1 transitions, and is known as the GDR.

For light nuclei the resonance has obvious structure, and this corresponds to transitions between specific states. These are modelled on the SM or modifications thereof.

You should note that the states in this GDR are **CN** states. That is, the energy of the exciting photon is shared by all the nucleons in the nucleus in a statistical way. The state is long-lived, and the decay is independent of the mode of excitation. Decay can be, as we have noted a few lectures ago, to any energetically accessible state in nearby nuclei, and the probability of decay via a particular channel will depend on the overlap between the GDR WF and the residual state +nucleon WF.

generally proton and neutron decay are common, although in heavy nuclei, proton decay is unlikely because of the coulomb barrier. As we mentioned earlier, the decay by say neutron emission will be statistical, the neutrons will be *boiled off*, and the energy spectrum will be something like:

The high energy neutron peaks correspond to decays that populate specific states in the residual nucleus.

Because of the collective nature of the GDR, the nucleons are continually interacting, and the details of the residual N-N interaction are lost. The interaction is dominated by **long-range effects**, so that study of this region of the photo-absorption cross section reveals only macroscopic details of the nucleus. E.g. its shape, the dependence of the energy on nuclear size, the location of the dipole states *en masse*.

The D**-resonance region** The other extreme to the collective GDR, is the Δ-resonance at about 300 MeV. Here the γ-ray wavelength is much shorter, and the interaction becomes predominantly with individual nucleons. This resonance is dominated by single-particle effects such as nucleonic or mesonic resonances. Study of photoreactions in this energy region is of interest for study of quantum sub-structure of the nucleon. And indeed we are involved is such studies with the MIT group.

Our current interest is the study of photonuclear reactions in the energy region between these two extremes of collective effects and nucleonic resonances…

the Intermediate Energy region. Residual interactions or Short-range correlation effects occur when two nucleons are close to each other. Their effects or masked in the GDR region, and not present in the Δ-resonance region. In the intermediate-energy region the nucleon has higher energy and is more likely to leave the nucleus without interacting on the way out (final state interactions). The study of interactions in this energy region is more likely to reveal the effects of short-range N-N interactions, unperturbed by collective effects.

You will notice that we have chosen the most difficult region to do experiments. The cross section is small and falls between 50 and 120 MeV. This means that we need to be pretty clever in designing the experiments.

- how we do the experiments
- what we expect to see
- what we learn

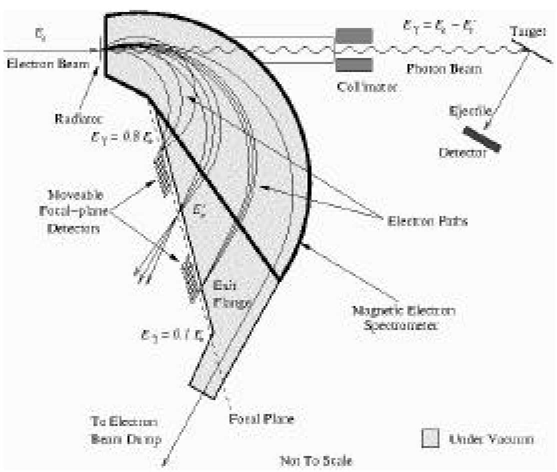
Experimental details
needs
- source of photons of known energy
- detectors for protons and neutrons
- means of determining the energies of protons and neutrons.

source of photons of known energy
We want photons of energies between 50 and 100 MeV. These don't grow on trees. Such photons can only be made by converting the energy of high energy electrons into EM radiation. This process is called *bremsstrahlung radiation*, literally *braking radiation*. You probably heard it mentioned in part 1 physics; it is the process whereby ordinary medical x-ray machines work.

A high energy electron from an electron accelerator falls on a thin high-z target (say Platinum). As the electron approaches a nucleus the coulomb force deflects it. This deflection angle depends on its impact parameter, the smaller the impact parameter the larger the deflection; just as for the Rutherford α scattering we studied in lecture 1. Because we are dealing with a quantum system, the energy lost by the electron in the acceleration occurring during the scattering process appears as a photon. It is clear that there is a larger chance of the impact parameter being large, the deflection and consequent photon energy being small. So that the resulting photons have a spectrum with a huge number of low-energy photons, and a very small number of high energy ones. The tip of the spectrum has an energy equal to that of the incident electron, and there are very few of these. They correspond to the electron approaching the nucleus head on, and experiencing the maximum acceleration.

$\boxed{\text{Draw spectrum}}$

So unfortunately we don't have a source of photons of known energy. Doing an experiment with this spectrum we would never know what energy photon caused the reaction. Physicists are pretty inventive, because we know not just what is a bremsstrahlung spectrum, but how it comes about. And that is why as engineers you have an advantage over straight engineering students. You should understand the why of phenomena, not just the phenomenon.



Because we know that for every photon produced there is a scattered electron, we can determine the energy of the photon by measuring the energy of the electron (this is easy since electron energies can be determined by bending them in a magnetic field).

$$E_\gamma = E_e - E_{scatt.}$$

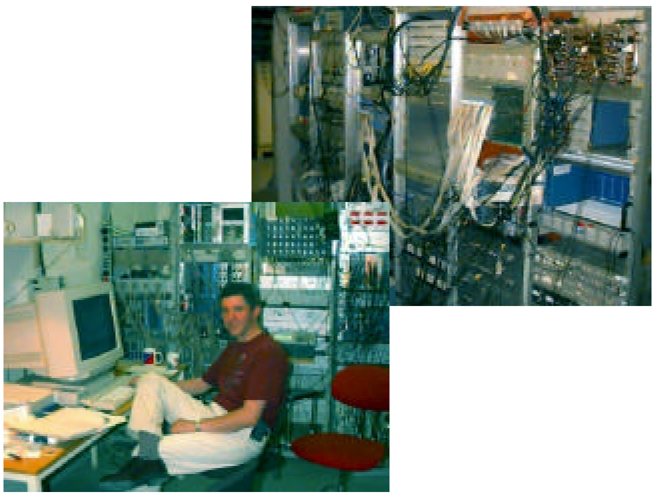
$E_{scatt.}$ is measured by momentum selection in a spectrometer, and depending on its radius of curvature hits one of say 100 small detectors on the focal plane of the spectrometer.

This is called tagging the photon. To utilise this we must be able to identify which electron that we detect is the one that interacted with our experimental target to produce the proton or neutron that we detect. This requires being able to time the detection of the reaction particle and the detection of the tagging electron within 10^{-9} sec.

Unfortunately most linear accelerators produce all their electrons in a time bunch of about 1 micro sec. 100 times a second. They produce about 10^8 electrons per second, so that the average spacing between electrons is much less that 10^{-9} sec. This tagging system could not be used until a way was developed to spread the electron beam out over all time. This required development of a stretcher ring. In essence this large circular ring forces the electrons by magnets to circulate. The circumference of the ring is such that it takes 1 microsec for the electrons to circulate. Thus the tip reaches the tail and we have a continuous beam of electrons that can be scraped off in a continuous way.

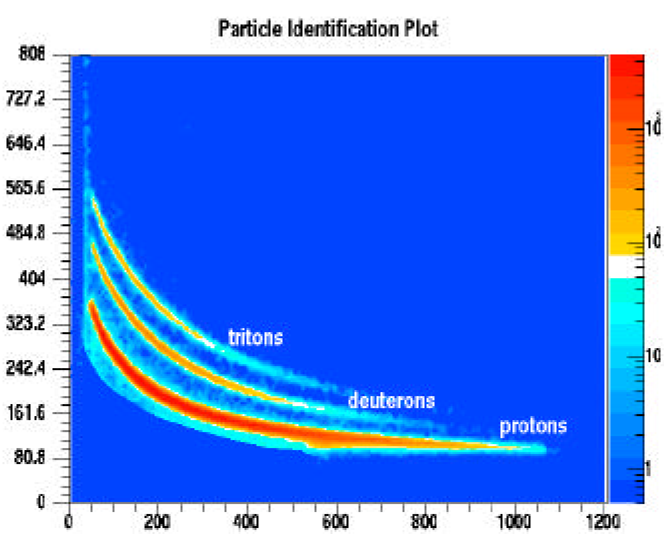
So now we have a known-energy photon.

Please don't imagine that this is as simple as I have told you. The problem of looking for these nanosec. Coincidences between 100 electron detectors and perhaps 30 reaction channels requires very sophisticated electronics.



detectors for protons and neutrons

We need to detect protons, and to measure their energy. This in fact is not too difficult. We use detectors like the NaI detectors you used in part 3 to detect γ-rays. Protons being charged ionize matter, and lose energy, so that they have a finite range in matter. If we do experiments at 100 MeV, and the BE of a proton is about 10 MeV, we need to be able to stop 90 MeV protons in our detectors. It turns out that about 8 cm of scintillator is enough. The ionization effects lead to light emission form the scintillator, and just as in your experiments, the amount of light is proportional to the energy of the proton.



There are significant complications however, since when our 100 MeV photons hit the sample they produce energetic electrons (lots of) which also ionize the scintillator. How can we tell if the light pulse we observe comes from a proton or an electron? Protons being heavier lose more energy per mm than electrons of the same energy. So we put a thin scintillator in front of the large detector. A proton might lose several MeV in this, but an electron will lose very little. Both then deposit the remainder of their energy in the detector. Here is a plot of the energy lost in the thin detector vs that lost in the big detector.

Detecting neutrons is not so easy. Neutrons have no charge, and we must rely on them interacting via a nuclear reaction. The reaction we use is scattering off hydrogen. The energy given to the proton in the collision allows it to ionise a scintillator and we can detect the neutron. Unfortunately the energy of the proton is not the same as that of the neutron, so although we know we have seen a neutron, we don't know its energy.

The energy is worked out by measuring the time between its production by the photon and the time it is detected (a few nanoseconds). So again we have a very tight timing requirement.

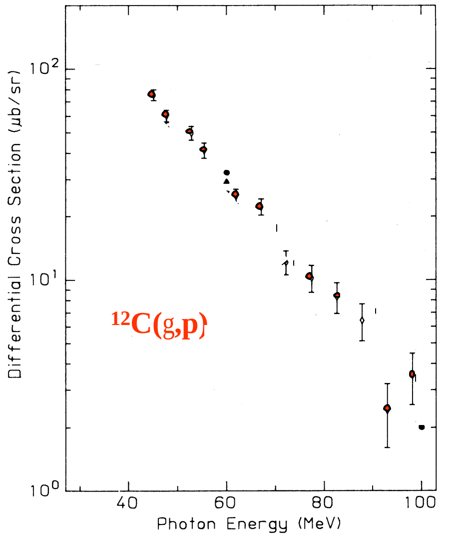
We discussed the regions of interest in the photo-absorption cross section. In particular the GDR region where the nucleus responds collectively. I indicated that our interest was in the Intermediate energy region where the photons has a sufficiently small wavelength that it interacts with individual nucleons. Importantly, the nucleon involved, gets out without much effort after the interaction, so we anticipate that we might see the effects of the Residual interaction, that bit of the nuclear potential that is not taken care of in the SM potential.

So what do we expect to see?
Firstly we expect that the high energy photon will not excite the nucleus as a whole. It is specific enough to probe individual nucleons within the nucleus.

More importantly we expect that it will only interact with the protons, since only protons have charge (the photon cannot see the neutrons). The simplest expectation is that it will interact with a proton and knock it out of the nucleus. This is called a Quasi-Free Knockout reaction.

Fig 1.3 GOK

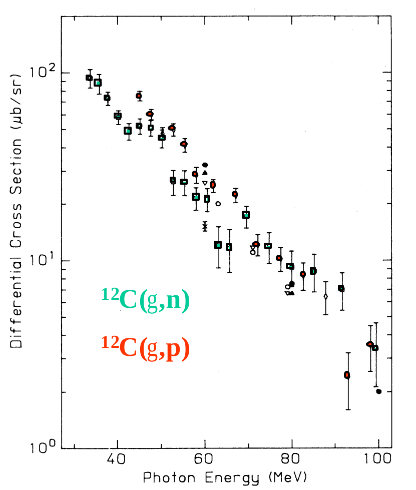
The rest of the nucleons are unaffected by this and the A-1 nucleons are considered spectators. This measurement has been done. We were one of the first groups to do it using tagged photons. What do we see?



It looks like what we expect. The magnitude falls as the energy increases. Unfortunately when we calculate the expected magnitude of the observed cross section, the calculated value is far too small. The reason for this is quite complex, but it has to do with conservation of momentum.

The photon brings in little momentum, but a lot of energy. It gives the energy to a proton, but the proton, which has mass, requires more momentum than the photon has. In order to conserve momentum, only protons that, because of their motion within the nucleus, have a large momentum (high momentum protons) can accept the photon's energy. There are very few of these. Hence this simple QFK model of the interaction seems to be in error.

An even more important worry is that when one measures the cross section for knocking out a neutron, it turns out that there are as many neutrons knocked out as protons. This is not allowed, since the photon does not see the uncharged neutron.



Well you might say that when the proton is on its way out, and it collides with a neutron so that it goes out. This interaction certainly happens, however the probability is too small to account for the large neutron cross section.

The answer seemed to lie in the observation that in almost 50% of cases both a proton AND a neutron were emitted. It seemed also that the angle between the proton and the neutron was close to 180 degrees. This led to the supposition that maybe p and n within the nucleus were correlated so that they looked like deuterons. (so called quasi deuterons). Certainly photons will interact with deuterons, and the QDM was proposed.

Fig 1.4

If there are N quasi deuterons in the nucleus, then the cross section for the reaction is simply

$$s_{qd} = L\frac{NZ}{A}s_{d}$$

This model has a great deal of appeal. It seems to account for the equality of the proton and neutron emission. The angular distribution seems about right, and it had a lot of adherents. But please note that from the point of view of letting us find out anything about the N-N potential, we have lost out. All the nuclear physics is tied up in the quasi deuteron. We don't probe it. Also, although it explains the equality of the γ,n and γ,p cross section, the absolute magnitude of both is fiddled with a normalising factor.

There is a third way to calculate the expected cross section. This is to try as far as is possible within the technological and physics limitations, to calculate the interaction of the EM field of the photon with **all the charges** and all the currents in the nucleus. That is to perform what is called a microscopic calculation.

Vugraph of Gari terms

Single-nucleon Measurements

At Tohoku University we have available a 100-MeV, 100% duty-cycle electron beam, and a tagging spectrometer. We have developed a set of liquid scintillator (NE213) neutron detectors which allow us to measure (γ,n) differential cross sections. Also available are several proton detectors including plastic and CsI detectors, which allow good resolution measurements of photoproton reactions. These tools, together with a fast data acquisition system and innovative techniques have lead to several reliable data sets. I want to discuss the ^{16}O(γ,n$_{o,1}$) and ^{16}O(γ,p$_{0,1}$) data taken at Tohoku.

Set up picture

The photoneutron measurements were made at photon energies from 40 to about 100 MeV. The detectors were placed at 45^{o}, 60^{o}, and 90^{o} so that the angular dependence could be determined. The neutron energy resolution was sufficient to resolve population of ^{15}O in the GS from several possible excited states. However it was not possible to resolve population of the +ve parity doublet at about 5 MeV from population of the 6.3 MeV state.

From these data one can derive the differential cross section for population of these states at the 3 angles. I will show only the cross section where the GS of ^{15}O is populated, as this is the easiest to compare with predictions. But first I want to interpolate the measurements of the $^{16}O(\gamma,p)$ made by Tony Bates, since they illustrate that the (γ,p) and (γ,n) cross sections are so similar, and also that the comparison with predictions becomes clearer when we see them together with the (γ,n).

$^{16}O(\gamma,p)$

These data were taken using plastic scintillators placed at 10 angles to the photon beam between 30^o. and 150^o. From the raw data we derived the differential cross sections for $^{16}O(\gamma,p)$ to several of the final states in ^{15}N. As well the AD, at specific photon energies can be found. Figure 1 shows the results for ^{16}O for both proton and neutron emission. Also included are data from Findlay

$\boxed{^{16}O(\gamma,no)\ (\gamma,po)}$

Note firstly how the proton and neutron cross sections are almost identical

What do these results tell us about the reaction mechanism? The Figure includes the comparison with three of the relevant predictions. The QDM, and two microscopic calculations. To first order the fits are all adequate. While it is true that the QDM tends to underestimate the proton cross section both at low and high energies, in the case of the (γ,n) there is little to choose between them.

Perhaps we need to look at a more constrained data set... the angular dependence of the cross section. This is shown in the next figure. Together with the data of O'Keefe and Bates, are included $^{16}O(\gamma,p_o)$ data from Findlay, and $^{16}O(\gamma,n_o)$ data of Goringer.

$\boxed{\text{AD for } ^{16}O}$

This is the AD of protons and neutrons to the respective GS, when the ^{16}O is excited to 60 MeV. Here the confusion becomes greater. For the $^{16}O(\gamma,p_o)$ reaction the fit by the microscopic calculations is far superior to that of the QDM. Contrary to our expectations the photoneutron AD is better fitted by the QDM. The microscopic calculations seem to overestimate the cross section and underestimate the forward peaking.

This was extremely frustrating, and it seemed to us that there should be a way to specifically test the predictions of the QDM by looking at the situation when BOTH a p and n are emitted.

We decided that the only way to differentiate the predictions was to study the $^{16}O(\gamma,pn)$ reaction by detecting the p and n in coincidence.

If we had sufficiently good resolution, and could obtain and adequate counting rate we could measure the cross section to specific states in ^{14}N. What would this tell us?

$^{16}O(\gamma,pn)$ figure

Remembering that the QDM considers that within the nucleus of ^{16}O there are p-n pairs looking like deuterons, with T = 0 and S = 1. The photon interacts with one of these pairs and leaves ^{14}N. Which states can it leave? If one takes the ^{16}O GS as being closed, the removal of a T=0 quasi-deuteron can produce the ^{14}N GS and other T=0 residuals; but never the T=1, 1st excited state at 2.3 MeV. On the other hand, microscopic models such as that of Ryckebusch would allow population of this state.

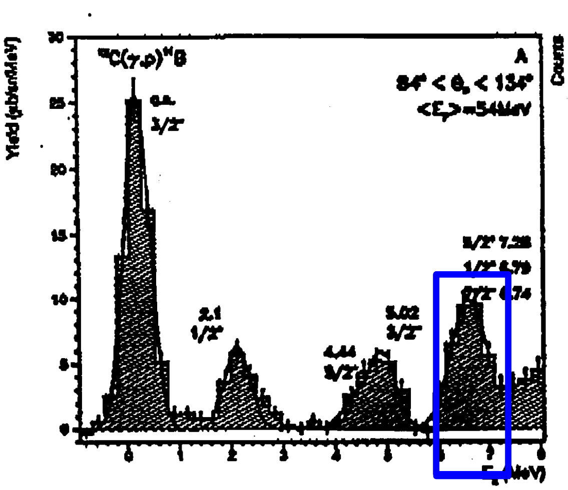
We decided to measure this reaction, however we failed! Although we had sufficient energy resolution so that the missinγ–energy spectrum should have resolved population of any of the low-lying states, the counting efficiency was abysmal. Fortunately, Leonard Isaksson did this experiment at Lund and has shown that this T=1 state in ^{14}N is not populated.

Lennart's data

So we must assume that the 2-body mechanism modelled by the QDM has some measure of truth.

However our (γ,pn) experiment was not a total waste of time; we did collect the proton spectrum, and this proved to be particularly interesting. Figure 3 is a recent result from Tohoku from Rogers thesis, which shows which states in ^{15}N are populated. The GS of course, the 6.3 MeV state, and importantly the doublet near 5 MeV. It turns out that if the QDM is correct, these two states near 5 MeV, which have a configuration which is essentially a neutron coupled to the T=1 1st-excited state in ^{14}N cannot be populated. So it would seem that although the (γ,pn) data suggests that the QDM has some validity, the (γ,p) data denies it.

While we were pondering this, the group at Lund University reported an interesting measurement of ^{12}C(γ,p). They measured the protons from ^{12}C(γ,p) with moderate resolution and observed population of +ve parity states near 7 MeV that, in direct analogy to the situation I described above, should not be populated if the QDM prevails. They concluded that this population was the result of photons interaction with pn pairs, however the pairs would need to have opposing spins, these would be T=1 quasi-deuterons, not the analogue of the true QD.



Wave function

One possible interpretation that we put forward was that at the energies at which the measurement was made, it was possible that collective effects could explain the results. Basically that the ^{16}O GS wavefunction is not a closed shell as you now know, but actually has an admixture of 2p2h in its configuration that would allow a single p to be removed from the 2s or 1d subshells to create the states in 15N.

We were not happy with the resolution of their experiment, even though it was the best possible available resolution. They seem to have made conclusions on the basis of data whose interpretation was questionable. A good physicist always knows his limitations.

It seemed that the only way to resolve this was to actually measure the $^{12}C(\gamma,pn)$ cross section directly. We would want to see if the state in ^{10}B that the ordinary QD (T=0) could not populate was in fact populated. Probably more realistically we wanted to get a better resolved photoproton spectrum . We already knew that we did not have a big enough neutron detector to make the $^{12}C(\gamma,pn)$ measurement. We therefore decided to find evidence of the excited states in ^{11}B following $^{12}C(\gamma,p)$ by observing de-excitation γ–rays from these states. The anticipation is that the γ–ray spectrum would resolve the +ve-parity doublet more cleanly than the published photoproton measurement. The reason for this is that the states near 7 MeV decay not only directly to the GS, but also via cascades, giving γ-rays that can easily be resolved.

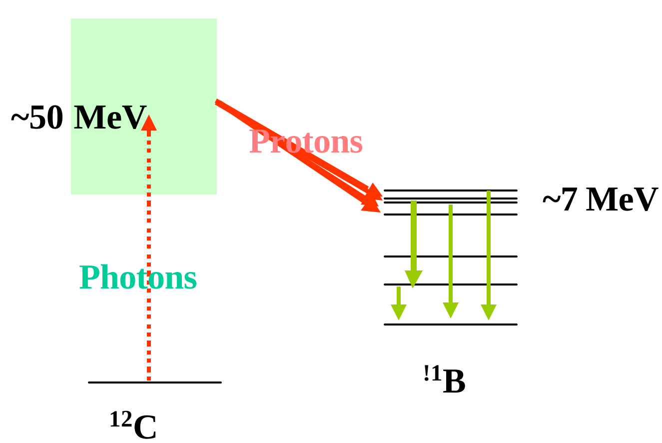
Alex picture showing cascades

A significant bonus is that by looking for de-excitation γ–rays following a proton trigger, we should also observe de-excitation γ–rays from states in ^{10}B; thus possibly allowing us to see if the T=1 state at 1.76 MeV was populated or not.

Alex expt.

- **Aim** To resolve the population of the 3 states near 7 MeV
  6.74 $7/2^-$
  6.79 $½^+$
  7.29 $5/2^+$
- **measure the proton spectrum to states in ^{11}B**
- **when a proton populates any of these states record any g-ray emitted**
- **knowing the branching ratios of the g-rays determine the population of the 3 states.**

This is not an easy experiment. One needs now to take a triple coincidence: we need to see which de-excitation γ-ray is in coincidence with which proton, which is in coincidence with a tagged electron.



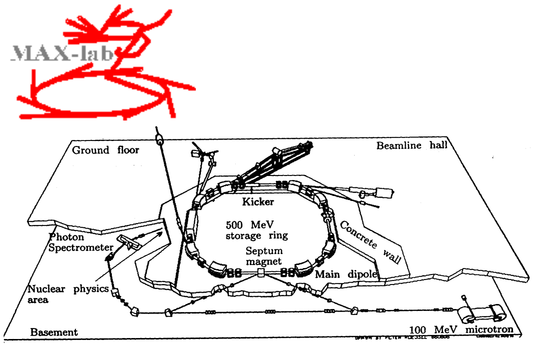
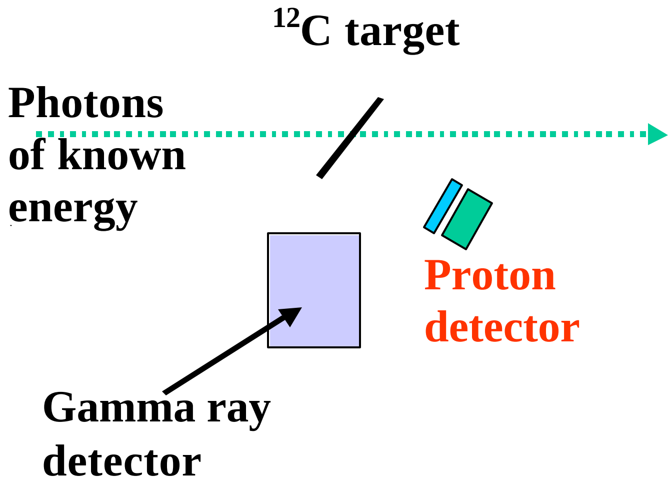


Figure 3.1: The layout of the MAX lab accelerator system.



What did he find?

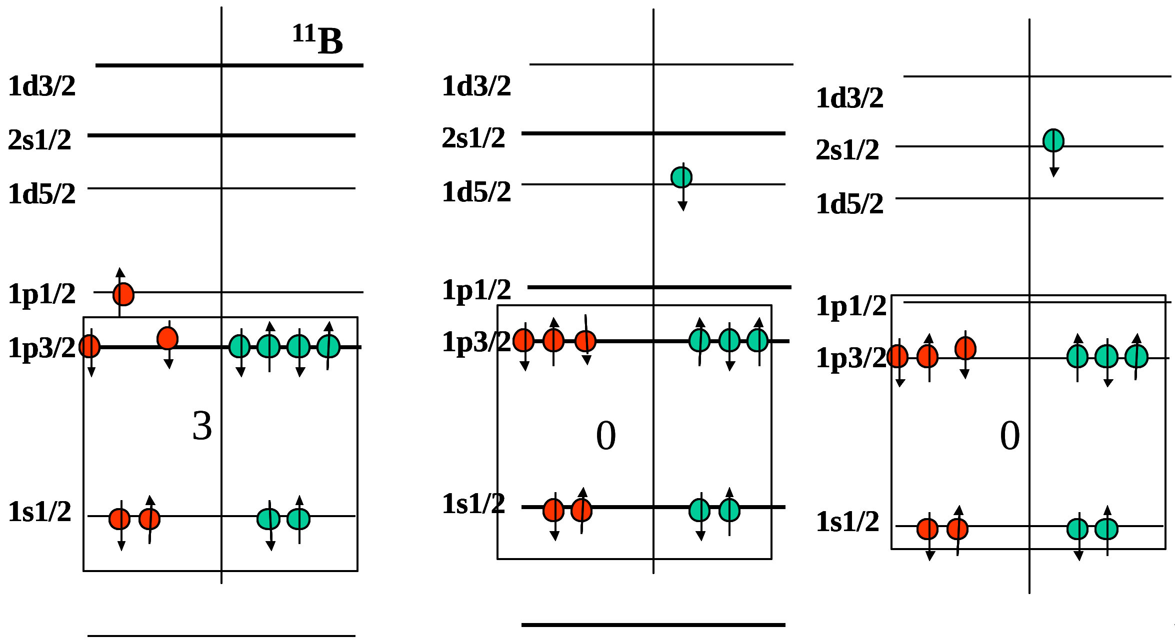
He found that the -ve parity state at 6.74 is populated about 3 times more strongly than the +ve parity states. Quite the opposite to the group from Gent University.

Why is this important?

- **Ockum's razor**. By misinterpreting their data, the Gent group introduced a complex reaction mechanism, not necessary.. Always choose the simplest explanation
- The -ve parity state is populated most strongly because its wavefunction is a single hole in the major term in the ^{12}C GS wavefunction.

- The smaller, but significant population of the +ve parity states shows that the ^{12}C GS wavefunction has significant admixtures, and if one wants to describe the interaction of a high-energy photon with ^{12}C, these need to be included in the theory.

7/2$^-$ 6.74 MeV **5/2$^+$ 7.29 MeV** **1/2$^+$ 6.79 MeV**



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reviously they had not. Now however we have had our theory colleague Jan Ryckebusch do an exact calculation and his results agree with Alex.

In other words if you want to explain the way in which a photon interacts with a nucleus, you need to consider all the charges, and all the currents that exist in the nucleus. This requires that you know the GS wavefunction, since it is this that describes the distributions.